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Slope Stability Analysis Using the Unsaturated Stress Analysis. Case Study

Loretta Batali[1] and Carastoian Andreea[2]

[1] *Technical University of Civil Engineering, Bucharest, Romania.*

[2] *Technical University of Civil Engineering, Bucharest, Romania.*

loretta@utcb.ro, carastoian.andreea@yahoo.com

Abstract

Paper approaches the problem of considering the unsaturation of soils above water table in the slope stability analysis, condition for obtaining realistic results in both cases of rainfall infiltrating into the soil mass and drainage for improving soil stability. It presents in its first part a brief review methods related to unsaturated stress analysis applied for slope stability analysis, such as Unsaturated phi-b, Unsaturated Fredlund, Unsaturated Vanapalli, Unsaturated Khalili and Unsaturated Vilar model. These methods are estimating in different manners the shear strength depending on soil unsaturated conditions. These methods are applied in the second part of the paper in a case study, presenting a site affected by landslides located in Cluj-Napoca, Romania. For the slope stabilization a siphon drain system has been proposed and installed. An experimental program started and is ongoing on site, compromising site monitoring of suction using jet fill tensiometers and laboratory testing. Site measurement of suction in presence of drainage system was used for perform slope stability analysis using SVSlope software and the embedded methods for estimating the increase in soil shear strength when passing from saturated to unsaturated state.

Keywords: unsaturated soil, slope stability analysis, siphon drain system, tensiometer

1 Introduction

Slope stability is largely affected by water-related changes in the soil mass. Obvious, there are number of possible factors that can lead to the instability of a soil slope. In general, earthen slopes remain stable unless there are changes in the pore-water pressures in the soil comprising the slope. Changes in pore-water pressure are generally the result of water infiltration related to the climatic conditions. Often it is the reduction in negative pore-water pressures in the upper part of soil that triggers slope instability (Fredlund and Rahardjo, 2007).

Several other authors (Bittelli et al., 2012) emphasized that the most important cause for shallow landslides is the decrease of matric suction after a rainstorm and the development of positive pressures

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above the water table. As soil shear strength increases with increasing soil matric suction, when suction becomes less negative the soil is more susceptible to failure (Bittelli et al., 2012).

As several field measurements showed, suction has a key role in maintaining the stability of slopes (Gavin and Xue, 2008). Therefore, modeling in the slope stability analysis the suction effect becomes mandatory for obtaining realistic results. Traditional saturated soil mechanic approach cannot solve the problem. Especially when a drainage system is implemented for ensuring slope stability, the negative pore-water pressure is permanent and highly influencing the safety factor.

Paper presents in the first part some generalities about methods used for stability analysis in unsaturated slopes, methods which will be later used for a case study. Case study presents an instable slope which is in process to be consolidated using siphon drains, thus by reducing pore-water pressure. Site measurements were performed regarding the suction and its evolution during the time. Then, several methods for unsaturated slope stability analysis were applied.

2 Unsaturated Slope Stability Methods

Slope stability analysis is a common element in the designing process of civil engineering projects. There are several possibilities for performing a slope analysis, for example:

- limit equilibrium methods (LEM) based on slice discretization of the soil mass, assuming various geometrical forms for the slip surface. As these are largely implemented into the engineering practice, they have been subject of evolution in the last years as introduction of unsaturated parameters or laws, application of modern optimization techniques based on genetic management of computations, multiple wedge analysis etc. (Tran and Srokosz, 2012);
- numerical methods using displacement-based finite element method (FEM), using various constitutive models, enabling to calculate the progressive failure and safety using "phi-c reduction" or "shear stress reduction" techniques;
- limit analysis approaches based on lower and upper bound theorems of classical plasticity (Tran and Srokosz, 2012);
- variation methods;
- probabilistic methods; etc.

In the following parts of the paper we will address only LEM.

For taking into account the soil shear strength modification due to suction evolution, several methods are available and implemented in commercial software. We will refer to and later apply some of the methods included in SVSlope software, which are estimating in different manners the shear strength depending on unsaturated soil conditions. These are: Unsaturated Phi-b, Unsaturated Fredlund, Unsaturated Vanapalli, Unsaturated Khalili and Unsaturated Vilar model. (SVOffice 2009)

The Unsaturated phi-b method defines the parameter ϕ^b as the angle defining the increase in shear strength for an increase in matric suction $(u_a - u_w)$. The unsaturated shear strength angle varies between 0^o and ϕ'. Fredlund and al. (1978) proposed the following equation (1), as the failure criterion for an unsaturated soil, expressed in terms of two stress state variables, the net normal stress $(\sigma - u_a)$ and the matric suction $(u_a - u_w)$ (Fredlund, 2005).

$$\tau = c' + (\sigma_n - u_a)\tan\phi' + (u_a - u_w)\tan\phi^b \tag{1}$$

where: - shear strength; c' - effective cohesion; σ_n - total normal stress; u_a - pore air pressure; u_w - pore water pressure; ϕ^b - unsaturated shear strength angle, generally taken equal to half of the effective friction angle value, in absence of other tests (Krahn, 2007).

The Unsaturated Fredlund method requires the entry of the soil-water characteristic curve (SWCC), depending on the volume of water present in the soil at a particular suction level. (Fredlund and Xing, 1994). This method makes use of Fredlund and Xing (1991) equation (2):

$$\tau_{ff} = c' + \left(\sigma_f - u_w\right)_f tan\phi' + (u_a - u_w)_f tan\phi'' \quad (2)$$

where: τ_{ff} - shear strength; $\left(\sigma_f - u_w\right)_f$ - net normal stress state with respect to the pore-pressure on the failure plane at failure; ϕ'' - friction angle associated with the matric suction stress state variable. In the following case study, was used a SWCC determinate based on Fredlund and Xing's equation and the available database in SVSlope (Fredlund and Xing, 1999).

The Unsaturated Vanapalli method depends also on the SWCC. Based on Fredlund and Xing equation (2), Vanapalli and Fredlund (1991) proposed a more general non-linear function, for modeling the unsaturated shear strength (3).

$$\tau = [c' + (\sigma_n - u_a)tan\phi'] + [(u_a - u_w)\{(\Theta^k)(tan\phi')\}] \quad (3)$$

where, in addition to eq. (1): k - the fitting parameter used for obtaining a best-fit between the measured and predicted values; Θ - the normalized water content. Later, Vanapali et al (1996) have proposed a modified equation (4) without using the fitting parameter, *k*.

$$\tau = \left[c' + (\sigma_n - u_a)tan\phi'\right] + \left[(u_a - u_w)\left\{\left(\frac{\theta_w-\theta_r}{\theta_s-\theta_r}\right)(tan\phi')\right\}\right] \quad (4)$$

where: θ_w - the volumetric water content; θ_s - the saturated volumetric water content; θ_r - the residual water volumetric content.

The Unsaturated Vilar method is not dependent on the SWCC as Fredlund's and Vanapalli's methods. This method allows defining a maximum cohesive strength. Rohn and Vilar (1995) proposed the following equation:

$$\mathrm{c}(\psi) = \mathrm{c}' + \frac{\psi}{\mathrm{a}+\mathrm{b}\psi} \quad (5)$$

where: $c(\psi)$ - the maximum cohesive strength (ultimate), depending on suction, ; c' - effective cohesion; *a* and b - fitting parameters; a = 1/tan(phi') and *b* = 1/($c_{ultimate}$-c').

The Unsaturated Khalili method allows modeling of the strength contribution of unsaturated soils. Khalili and Khabbaz (1998) have extended Bishop's equation (6) as follows:

$$\tau = \left[c' + (\sigma_n - u_a)tan\phi'\right] + \left[(u_a - u_w)\{(\chi)(tan\phi')\}\right] \quad (6)$$

where: χ - parameter depending on saturation grade, with values between 0 and 1. An empirical formula has been suggested for the parameter $\boldsymbol{\chi}$ (7):

$$\chi = \left\{\frac{(u_a-u_w)_f}{(u_a-u_w)_b}\right\}^{-0.55} \quad (7)$$

where, $(u_a - u_w)_f$ is the matric suction at failure conditions.

All these methods will be applied for the following case study.

3 Case Study

3.1 General Description

This case study presents a site affected by landslides located in Cluj-Napoca city, in center of Romania. The project to be developed on the site is an industrial park. The site has approx. 80 ha and it is located on Hoia hill, on its Northern side, hill which is affected by numerous instability phenomena on approx. 15 % on the surface, while other 25 % have high instability potential. The slope of the hill in the site area is 12°. Geotechnical investigations performed in the area concluded that the main cause of instability phenomena is the excess pore-water pressure due to both rainfall infiltration and groundwater. Existing landslides were classified as shallow ones, their maximum depth reaching 4–5 m. The preliminary analysis performed for design purposes showed possible instability for seismic conditions (the site is characterized by a design seismic ground acceleration a_g = 0.1g) without drainage measures. Therefore, a drainage system based on siphon drain network was designed and lately implemented.

3.2 Geotechnical Characteristics

Table 1 presents the main geotechnical parameters of the strata. Ground water was found at -5.20 m.

Characteristics	Man-made fill (0-1.00m)	Silty Clay (1.00-4.10 m)	Sandy Clay (4.10-5.70m)	Green-Brown Loam (5.70-6.40m)	Grey Sandstone (6.40-7.50m)	Marl (7.50-9.40m)
Water content, w(%)	17.42	18.78	16.22	16.85	16.54	20.92
Plasticity index Ip(%)		17.14	19.73	20.04	19.48	28.18
Unit weight γ (kN/m^3)	17.25	18.00	20.00	19.00	22.00	19.83
Consistency index, Ic		0.9	1.05	1.05		1.06
Saturation degree, Sr	0.54	0.65	0.54	0.65	0.64	0.87
Oedometric modulus E_{oed} (MN/m^2)	4.683	7.014	10.718	11.434	8.879	10.958
ϕ_k (°)	7	10	11	15	34	12
c_k (kPa)	10	14	15	40	55	73

Table 1: Geotechnical data (characteristics values)

3.3 Site Activity

An experimental research program has been implemented for this site consisting of:

- 3 boreholes of 1.70 m depth for monitoring the vadose zone;
- 3 jet fill tensiometers were installed in the boreholes at depth varying from 1.30m to 1.70m, in order to monitor suction values before and after siphon drains installation (see fig. 1);
- laboratory testing on samples taken from boreholes, both in saturated and unsaturated state, for determining SWCC (at least for targeted suction range) and mechanical characteristics of soil (Note: the laboratory testing is still in progress and will not be referred to within this paper).

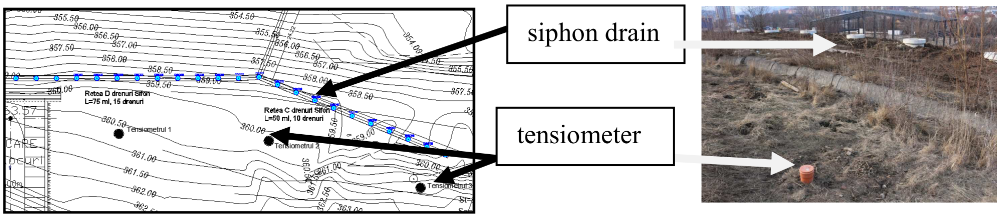

Figure 1: Tensiometers position on site - detail and the siphon drain line

In the following figures are presented the measured suction values, as recorded by tensiometers.

It can be seen that the maximum suction recorded with drainage system in function was of -20 kPa, compared to -7.5 kPa before its installation. This conclusion is not a final one, as monitoring should be continued and further conclusion will be drawn.

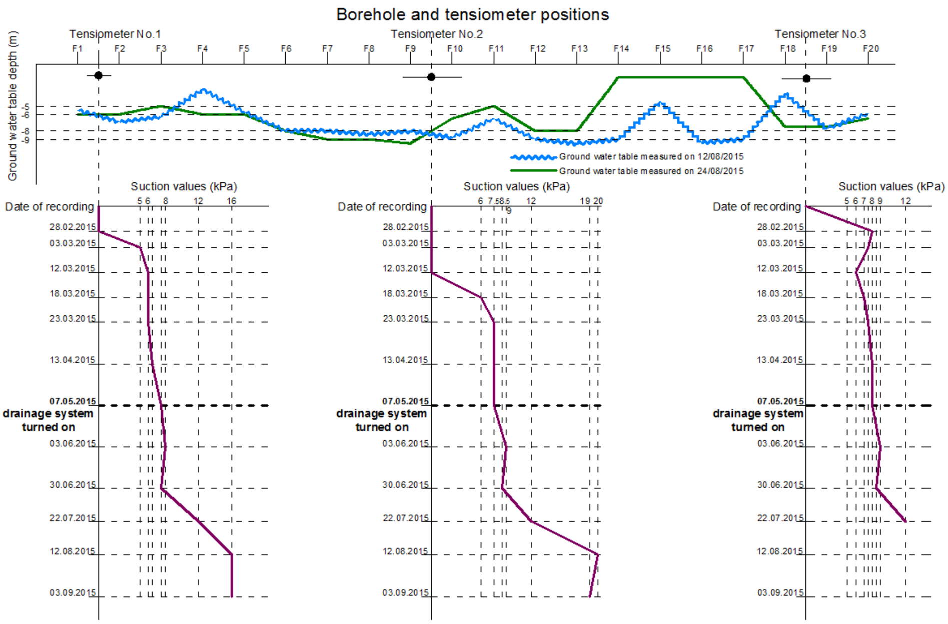

Figure 2: Measured ground water table and suction values

3.4 Slope Stability Analysis

For the conceptual understanding of the phenomena, five scenarios were analyzed:

1. Initial state, with ground water table at 5.20 m bgl, static conditions.
2. Initial state, as above, seismic conditions.
3. Saturated slope, presumably after rainfall with ground water table at 1.00 m, static conditions.
4. Saturated slope as scenario 3, seismic conditions.
5. Siphon drains in function, including maximum measured suction, seismic conditions and ground water table at -8.50 m bgl.

For all scenarios were performed slope stability analysis using SVSlope software - various methods (as describe in chapter 2 here above) for estimating unsaturated soils shear strength. For the slope stability analysis itself were used 6 analysis methods (Fellenius, Bishop, Janbu Simplified, Spencer, Fredlund's GLE (General Limit Equilibrium) and Sarma), 5 of them being common and well known. Details about Fredlund's GLE method can be found in SVSlope manual. Taken into account the site lithology and specific, as well as site observations, Non circular failure surfaces were used, as defined by the user. The slope model is shown below (fig.3):

For the purposes of this paper will be presented more in detail only scenarios 4 and 5 comparing the saturated slope situation and the one after drainage, in seismic conditions. All results are presented in Table 2. Figures 4 present the results using Mohr-Coulomb model for scenarios 4 and 5.

One can note that for a completely saturated slope after a rainy period of time and in seismic conditions (which is a common hypothesis for slope stability analysis in seismic areas) the factor of safety (FoS) is largely below 1 without drainage measures, while with drainage method (siphon drains) is increasing up to 1.200. These values are obtained using characteristic values of geotechnical parameters, therefore 1.2 can be considered in some cases insufficient, depending on design requirements.

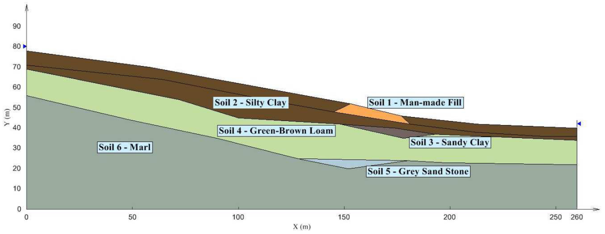

Figure 3: Slope model

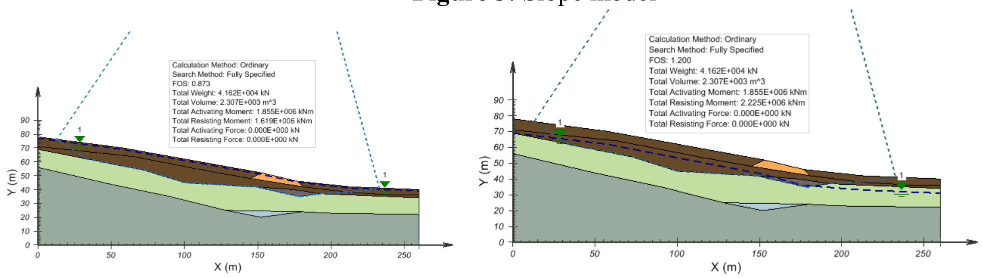

Figure 4: Scenario4 - seismic cond. - GWT=-1.00m - Mohr-Coulomb method **Fos min = 0.873** and Scenario5 - seismic cond. - with drainage - Mohr-Coulomb method **Fos min = 1.200**

One can note that for a completely saturated slope after a rainy period of time and in seismic conditions (which is a common hypothesis for slope stability analysis in seismic areas) the factor of safety is largely below 1 without drainage measures, while with drainage method (siphon drains) is increasing up to 1.200, which can be acceptable in seismic conditions if geotechnical parameters were used as design values.

When considering unsaturated properties for soils above the ground water table, using the previously described methods implemented into the SVSlope software for estimating the unsaturated shear strength, results are generally improved in terms of safety, as it can be seen from the synthesis of results in Table 2. A suction value of -20 kPa was introduced in the model for scenario 5, according to the maximum value recorded on site. Here below are presented only graphical results for 2 methods which offered the minimum and maximum factor of safety –Unsaturated Fredlund's and Vanapalli's methods (fig. 5). All other results are given in Table 2.

Analyzing all results in Table 2 it can be easily observed that in absence of drainage the slope is not stable and even with the drainage in function the safety margins are not sufficient in some cases. Thus, other consolidation measures should be (and have been) considered.

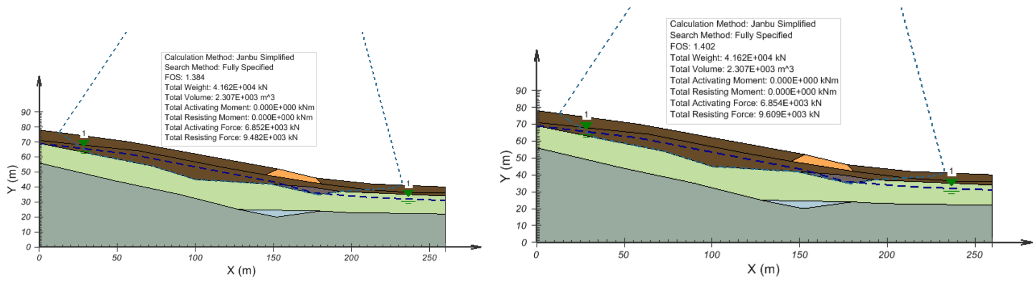

Figure 5: Scenario5 - seismic cond.-with drainage - Unsaturated Fredlund method - **Fos min = 1.38** and Scenario5 - seismic cond. - with drainage - Unsaturated Vanapalli method **Fos min = 1.402**

Obvious, a larger unsaturated zone, possible with increased shear strength parameters, (if such increase is considered), has a favorable effect and the factor of safety is increasing. For the studied case the minimum difference was recorded for Phi-b method (14%), while the highest one (18%) for Vanapalli's method. However, this may not be the case in other site conditions.

Unsaturated Phi-b method can be considered as the safest one, as ϕ_b value can be determined in laboratory or by applying the empirical rule (half of effective friction angle value) and also it is easy of use. (Krahn, 2007) Fredlund and Vanapalli methods depend on SWCC. The complexity of the additional curve parameters may slow down the calculation but Fredlund and Xing equation is excellent for the evaluation of unsaturated soil conditions. Vilar's method allows modeling the strength contribution of unsaturated soils.

Scenario	Mode	Method	Fellenius	Bishop	Janbu S	Spencer	GLE	Sarma
Scenario1	Static	Mohr-Coulomb	1.175	1.199	1.171	1.208	1.202	1.207
Scenario 2	Dynamic	Mohr-Coulomb	0.940	0.960	0.937	0.966	0.962	0.962
Scenario 3	Static	Mohr-Coulomb	1.091	1.117	1.090	1.125	1.120	1.125
Scenario 4	Dynamic	Mohr-Coulomb	0.873	0.894	0.872	0.900	0.896	0.901
Scenario 5	Static	Mohr-Coulomb	1.499	1.522	1.485	1.531	1.524	1.531
Scenario 5	Dynamic	Mohr-Coulomb	1.200	1.217	1.188	1.225	1.219	1.225
Scenario 5	Static	Phi-b	1.711	1.730	1.690	1.741	1.732	1.740
	Dynamic	Phi-b	1.369	1.384	**1.352**	1.393	1.386	1.392
	Static	Fredlund	1.753	1.771	1.730	1.782	1.773	1.781
	Dynamic	Fredlund	1.402	1.416	1.384	1.425	1.419	1.425
	Static	Vanapalli	1.776	1.794	1.752	**1.806**	1.797	1.805
	Dynamic	Vanapalli	1.421	1.435	1.402	1.444	1.437	1.444
	Static	Vilar	1.739	1.757	1.716	1.768	1.760	1.767
	Dynamic	Vilar	1.391	1.406	1.373	1.415	1.408	1.414
	Static	Khalili	1.766	1.784	1.743	1.795	1.786	1.794
	Dynamic	Khalili	1.413	1.427	1.394	1.595	1.588	1.435

Table 1: Synthesis of all results

It can be discussed for this particular case if the resulting factors of safety are acceptable or not, if the drainage has reached its maximum efficiency or if other additional measures should be taken, but these aspects are beyond the scope of this paper. Even if the laboratory testing program scheduled for this study is not very extended, when ready will allow refining the shear strength parameters and determine specific unsaturated soil parameters, based on SWCC and on shear test results, being so able to verify the estimated parameters within SVSlope.

As well, a numerical modeling using FEM could be useful for comparing the numerical predictions with the measured values and this will be performed further.

4 Conclusions

Considering the unsaturated properties of soils above water table in slope stability analysis allow to obtain more realistic results and to assess the efficiency of methods such as drainage. However, the availability of all unsaturated parameters is scarce and in the large majority of cases designers prefers to perform analysis only in saturated conditions for obtaining the minimum possible value of the global safety factor. Or, if unsaturation cannot be avoided, as in presence of drainage, designers need a simple method for estimating the shear strength parameters in unsaturated conditions. Databases included or not in commercial software can, of course, be useful in case of lack of tests. Some methods are now available for estimating the increase in shear strength due to increasing in suction and some of these were used in this paper.

The paper has reviewed briefly the available methods and then applied them for a case study. In the case study an unstable slope has been consolidated using mainly drainage measures (siphon drains), whose efficiency was assessed using suction measurement on site and by re-evaluating the slope stability based on measured suction value and on introducing estimated shear strength parameters for unsaturated soils. Further research is currently ongoing, related to laboratory testing, which will allow verifying at least some of the estimated parameters.

Stability analysis performed using 6 different and current methods of analysis and also 5 specific unsaturated methods, using SVSlope software, showed for the studied case that improvements of the slope stability was obtained. Drainage has proven to be effective and leading the slope into a marginal safety domain, which can demand further consolidation measures. Anyhow, consideration of only drawdown of water table couldn't correctly model the real situation.

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